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SPACE SOLAR CELLS - HIGH EFFICIENCY AND RADIATION DAMAGE

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ABSTRACT

In June 1979, a Third Solar Cell High Efficiency and Radiation Damage Meeting was held at the NASA Lewis Research Center. Sixty-eight people representing 10 government agencies, 16 companies and 10 universities attended. Papers and workshop sessions were held covering the following areas: High Efficiency Silicon Solar Cells, Silicon Solar Cell Radiation Damage, GaAs Solar Cell Performance and 30 Percent Conversion Devices. The focus was on space use of these cells. The thrust of the meeting was to assess the present status of work in these areas and to discern future trends and directions. The results of this meeting will be presented in this paper.

INTRODUCTION

The Third Solar Cell High Efficiency and Radiation Damage Meeting was held at the NASA Lewis Research Center on June 13 and 14, 1979. The objective of this meeting was to assess the progress and status of efforts to increase the end-of-life efficiency of solar cells for space use. These meetings are intended to serve as forums in which the experts in photovoltaics can express their individual and collective judgements on suitable, attainable goals for space solar cells, the barriers remaining, and the most viable approaches past these barriers toward the goals. Both paper and workshop sessions were held on the following topics: high efficiency silicon solar cells, silicon solar cell radiation damage, GaAs solar cell performance and radiation damage and 30 percent devices. The 68 attendees represented 10 government agencies, 16 companies and 10 universities. It is the purpose of this paper to summarize the key results of that meeting and to present the important conclusions and development trends that surfaced.

HIGH EFFICIENCY SILICON SOLAR CELLS

The participants concluded that an efficiency goal of 18 percent AMO is still reasonable. Open-circuit voltage was concluded to be the single remaining barrier to achievement of the 18 percent efficient silicon solar cell. Although many theoretical studies predict that voltages of 0.7 V are possible in 0.1 Ω-cm material, experimental results fall far short of that goal. After analysis of experimental data, three primary mechanisms were believed to account for the reduced performance - bandgap narrowing, Auger recombination and surface recombination velocity. Recently Lanyon (1) has produced a comprehensive theory that confirms the presence of bandgap narrowing and unifies all the experimental work. Based on his results, cell designs which overcome this limitation can now be created. A second mechanism, Auger recombination, was believed to dominate minority carrier lifetime in heavily doped silicon. Recently, Gatos (2) has used an electron beam of variable energy to explore the response of the emitter and base region of solar cells. As shown in figure 1, 5 keV electrons were used to generate current in the emitter, while 45 keV electrons were used to generate current primarily in the base region. The current collected is proportional to the minority carrier lifetime. Theory predicts that the normal Shockley, Read, Hall recombination processes lead to lifetimes (and hence currents) which decrease with decreasing temperature. This performance is shown by the 45 keV beam which penetrates well into the base region. It can be seen that the current induced by the 5 keV beam increases with decreasing temperature. This indicates that lifetime in the emitter region increases with decreasing temperature which is characteristic of Auger recombination. These and other data thus seem to strongly support Auger recombination as the second dominant mechanism.

In light of these mechanisms, Wolf (3) has reexamined the maximum achievable efficiency. His studies have resulted in new cell designs, as shown in figure 2. Key design features include: oblique penetration of light and total internal reflection, base and emitter widths narrow compared to the respective diffusion lengths, and relatively low dopant concentrations in both base and emitter. Using this design, which represents a tradeoff between collection efficiency and voltage, AMO efficiencies near 20 percent were projected.

Efforts to overcome the limits to open-circuit voltage have produced four different designs, all of which have achieved voltages near 0.65 V. These are shown in figure 3. Although all were made from 0.1 Ω-cm p-type base material, the means by which the emitters were formed all differed. Also, the design philosophies and mechanisms being studied for each of these cells were different. Briefly, the oxide charge induced, high-low emitter cell (OCLI-HLE) (4) was designed to take advantage of a small diffusion length to emitter width ratio and controlled sur-

face recombination velocity. The ion implanted cell (5) utilized a shallow junction with tailored profile to minimize bandgap narrowing effects and passivated surfaces. The diffused junction cell (6) used a deep junction to reduce surface effects and with controlled surface concentrations to reduce bandgap narrowing effects. The min-MIS cell (7) reduces bandgap narrowing and surface effects. All designs were successful to some degree in reducing either the base or the emitter component of the reverse saturation current (I_o) or both. The OCI-HLE cell appears to be primarily controlled by the emitter I_o while the ion implanted and the diffused cells appear to have significant base control. No results have been published on the min-MIS cell I_o components.

Analyses of the performance of these cells has led to a further understanding of the voltage controlling mechanisms. However, rather than shrinking, the list of voltage controlling mechanisms has increased. In addition to the well-known factors of bandgap narrowing, Auger limited lifetimes, and surface recombination velocity, mechanisms such as minority carrier diffusivity reductions, matching of dopant to lattice and band narrowing due to junction field were introduced. The growing list of mechanisms underscores the need for a focussed attack on the problem. In summary, in view of the significant progress made in increasing cell voltages and progress in our theoretical understanding, the participants concluded that 0.7 V is still a reasonable goal and that continuation of the basic approaches undertaken to date were still warranted.

Although the primary focus of this effort is to produce a high voltage cell at the beginning-of-life, is also important to consider the radiation tolerance of experimental structures. This challenge of radiation tolerance separates space high efficiency solar cell efforts from similar terrestrial efforts. Figure 4 shows results (8) of radiation testing of samples of the experimental OCI-HLE, ion implanted and diffused junction cells. The loss in output is greatest for the OCI-HLE cell that had been exposed to X-rays used in measuring diffusion length. Its companion, not exposed to X-rays, showed the next greatest loss. The ion implanted and diffused cells suffered comparable damage that was at a level expected for 0.1 Ω-cm material. They, however, degrade far more rapidly than the 10 Ω-cm cell. Spectral response measurements show that both OCI-HLE cells loose their blue response during irradiation. The use of a 10 μm wide n-type emitter layer is responsible for this loss. Because the damage coefficient in n-type materials is about one order of magnitude greater than p-type material and because 75 percent of the incoming light is absorbed in the emitter, increased susceptibility of this type of cell to radiation is expected. Careful redesign of the cell with substantial reductions in emitter width would largely overcome this problem (4). However, sensitivity of the charged oxide to radiation damage as demonstrated by the X-ray results suggests that an alternate technique (such as diffusion or ion implantation) be found for forming the high-low junction in the emitter.

Alternate concepts to produce high efficiency cells that are resistant to particulate radiation include various types of rear junction cells such as the back junction cell (p^+-p-n^+ or p^+-p-n-n^+) and the interdigitated back contact cell. The back junction cell seeks to overcome the radiation sensitivity of the OCI-HLE type cell. However, as shown by the calculations depicted in figure 5, (9), the backwall cell is also sensitive to radiation unless designed carefully. Also included in figure 5 are experimental results for a tandem junction interdigitated back contact cell (10). These results show that the backwall cell can achieve good radiation tolerance provided the p-type layer is either thin (<50 μm) or made from high resistivity (∼100 Ω-cm) material. It should also be noted that this study did not incorporate features that would produce high voltages, rather it was a study to define general limits of backwall cells. The tandem junction, interdigitated back contact cell appears to degrade in much the same way as calculated for the back junction cell, hence similar design considerations should apply. In view of these results, the options for radiation tolerant, high performance cells seem to be rather diverse. It appears desirable to have heavily doped material to aid in achieving high voltages by suppression of the base layer reverse saturation current, but this produces a radiation sensitive cell. On the other hand, the combination of thin cells with intrinsic or high resistivity material offers radiation tolerance but their efficiency potential is largely unexplored experimentally. The calculations by Wolf (3) offer and intermediate position and sensitivity of those cells to radiation has not been studied.

Preliminary calculations (11) show that indeed a 50 μm n-i-p cell can have both radiation tolerance and high voltage and efficiency. Initial efficiency of the n-i-p cell was 18 percent. This cell lost only 15 percent of its output after a radiation dose equivalent to seven years in synchronous orbit. In view of these results, one of the conclusions from the Solar Cell High Efficiency and Radiation Damage Meeting was that high beginning-of-life and high end-of-life efficiencies were not incompatible and that both the n-i-p cell and the vertical junction cell might achieve this goal.

Another unique, space-related problem is control of cell absorptivity. The greater the absorptivity the higher the cell operating temperature in space where only radiative cooling is possible. Cells with textured surfaces operate at temperatures high enough to cancel out their performance advantage over nontexturized cells. Thus, control of absorptivity by use of back surface reflection and planar cells with antireflection layers made from two or more compounds represent a growing area of interest.

The use of ion implantation and various so-called "cool" processing steps that do not leave cells exposed to high temperatures for long times are also important. Laser and electron beam processing fall into this category. Additional advantages of all these technologies is their ability to tailor emitter profiles and to produce structures and doping levels not possible by other methods. These techniques will continue to be important in the quest for higher silicon solar cell efficiency.

SILICON SOLAR CELL RADIATION DAMAGE

The primary focus of current efforts in silicon solar cell radiation damage reduction has been on identification of the atomic composition of the primary radiation induced defects. By this approach, it is believed that means can be found for prevention of critical defect formation or healing of the most injurious defects. The first step in this process is identification of the defects created by 1 MeV electron irradiation that reduce minority carrier diffusion length in p-type silicon. Weinberg (12) has combined various experimental measurements to determine that three defects are responsible for the drastic loss in minority carrier lifetime with fluence. These defects are shown in figure 6, along with their suspected atomic composition (13, 14). It is clear that one defect contains boron, one contains carbon and the third consists only of radiation induced vacancies. It is these defects, operating in concert, that produce the variation of damage coefficients with resistivity, as shown in figure 7. The inset of figure 7 shows how the production rates of two key defects change with resistivity (13). It would appear possible to substantially reduce radiation damage in silicon by reducing or eliminating boron, oxygen and carbon from the host silicon. The increased radiation tolerance of low oxygen content, float zone refined silicon suggests the validity of this approach. An additional approach is to replace boron with an alternate dopant (i.e., gallium). Some exciting results have been obtained in gallium-doped silicon with low carbon and oxygen content. Under irradiation, this material, which is doped to a resistivity 0.1 Ω-cm, exhibits the radiation behavior equivalent to 2 Ω-cm silicon. Whether this result is due to the presence of gallium or to the reduced carbon and oxygen content is not known at this time. Finally, use of a mobile dopant which could heal the radiation-induced defect centers in attractive. This possibility has prompted the reinvestigation of lithium as a dopant. However, now the lithium is added to p-type silicon where it acts electrically as a counterdopant since it is a donor in silicon. Preliminary results show room temperature annealing of diffusion length which suggests healing of the radiation induced damage. Annealing kinetics and effect of lithium gradient are complex.

In the event that direct frontal assult on the radiation-induced defects does not succeed, an alternate approach to healing of radiation damage will be needed. In fact, when mission times of 20 to 30 years in synchronous orbit with virtually no loss in power are discussed, annealing may become essential. The thermal annealing of silicon is rather complex as shown in figure 8. These data on 0.1 and 2 Ω-cm cells were obtained at two laboratories (15, 16) and is reported in terms of the unannealed fraction of short-circuit current (I_o-I_T/I_o-I_o) where I_o is the current prior to irradiation, I_T is the current being annealed at temperature T, and I_o is the current after irradiation. Both results are consistent. The reverse annealing phenomena shown at temperature between 200° and 350° C is reproducible.

Clearly, the origin of the reverse annealing phenomena is to be found in the behavior of the radiation induced defects with temperature. DLTS studies (13) have given great insight into the change of defect concentrations with temperature. Such a result is shown in figure 9. These data, when combined with appropriate cross sections for recombination (12), will reproduce the data shown in figure 8. The center responsible for the reverse annealing is the $E_V + 0.3$ (B-O-V) level which is the offspring of the $E_c - 0.27$ (B-O) center. Elimination of either of these two centers would offer the possibility of producing a silicon cell which can be annealed at temperatures of 200° C instead of 450° C. It is clear that understanding radiation damage from an atomic level is producing significant results.

For annealing in space, the means for providing thermal annealing may be impractical. The laser may offer ideal source of energy for such annealing situations. Preliminary studies show that laser annealing does work. A variety of laser sources have been used from ruby to Nd:YAG. Energy deposition is brief and recovery of damage depends on factors such as laser pulse-width, duration, amount of damage and material resistivity. Primary problems are stress in the silicon and damage to cell-coverglass combinations. In order to bring the promise of this technique of fruition, more work aimed at understanding the basic mechanisms of the process will be needed.

In general, the feeling at the meeting was that great progress has been made in understanding radiation damage and its healing and that future work should continue to focus on basic defect and material studies.

GALLIUM ARSENIDE SOLAR CELL PERFORMANCE AND RADIATION DAMAGE

A variety of gallium arsenide solar cell designs for space use are being actively pursued at this time. The most highly developed of these is the Hughes Research Laboratories (HRL) 2x2 cm heteroface p-n AlGaAs-GaAs solar cell (17). It has a nominal junction depth of 0.5 μm and achieves efficiencies above 17 percent in production. Increasing attention is being devoted to development of the AMOS-cell by JPL (18) and the n-p homojunction cell by the Lincoln Laboratory

(19). The AMO3 cell has achieved AMO efficiencies of 14 percent with cell areas of 1 cm^2. The n-p homojunction cell has produced AMO efficiencies of 17 percent in 1/2 cm^2 sizes and nearly 16 percent in 4 cm^2 sizes. The radiation tolerance of these cells depends on junction depth. Figure 10 shows the comparison of several Hughes cells with the Lincoln Laboratory (LL) cell. The effect of reduced junction depth is apparent. However, the two cells are basically different as the one (HRL) has a window layer and an n-type substrate. The other (LL) has no window and a p-type substrate. With development, the latter cell may result in a more radiation tolerant cell because of longer minority carrier diffusion length in p-type GaAs material. However, the diffusion length damage coefficients in p-GaAs are not known. Practical limit for the shallowest junction in the HRL cell is about 0.3 μm due to the fabrication technology. These future development trends seem to favor the homojunction cell fabricated by chemical vapor deposition. The future potential and role of the AMOS cell is not clear. Cell performance seems to depend on control of voltage and oxide stability.

Of significant interest is the ability of the GaAs solar cell to be annealed at temperatures near 200° C. Figure 11 shows some of the interesting results obtained by NASA Langley (20). It can clearly be seen that almost complete (98 percent) recovery of the current is effected by heating for a few hours at temperatures around 200° C. The fluence was 10^{15} e/cm^2. Recovery of power was not quite as great in this study and that done by JPL (21). It appears that additional work on high temperature contacts will be required to bring this annealing opportunity to fruition.

These results, and additional calculational studies (20), indicate that operation of GaAs cells near 200° C in space could continuously anneal the radiation induced damage and hence significantly reduce the effect of long term electron irradiation. This finding prompted participants of the conference to recommend that the use of sunlight concentration be carefully explored. Participants also concluded that maximum GaAs cell efficiencies above 20 percent are possible and that space application of these cells is justified.

However, they believed that several major areas of concern remain. Pilot production of a significant number of GaAs cells is needed so that full space qualification and testing can be conducted to generate confidence in the reliability of these cells. Major technological problems that need to be solved are the cell electrical contacts (metallurgy, bonding, and interconnect problems) and optimization of the antireflection coating. It would be desirable to have a supply of cells made under well-controlled conditions to ensure uniformity and reproducibility. Cells made under "research" conditions would not be adequate to meet this need.

Participants also recommended that, due to their attractive features, homojunction cells produced by the CVD process should be developed in parallel with the present LPE capability to offer an alternative. The cost and availability of Ga and GaAs was discussed. The availability of Ga was not considered to be a problem in the foreseeable future for space applications. Alternatives to the expensive GaAs substrates are Ge and Si. Of these, silicon offers an attractive possibility and has a number of advantages over Ge in terms of cost, availability and weight. Thus, development of GaAs cells based on Si substrates should also receive attention. The final conclusion was that the GaAs cell is a viable contender for space applications and its brightest future lies just ahead.

30 PERCENT DEVICES

The participants of the workshop were enthusiastic in their conclusion that 30 percent AMO efficiencies represent a reasonable target. Calculational support for this position is shown in figure 12 (22). It indicates that a two-junction cell operating at a temperature of 400 K and 1000 suns concentration could achieve an efficiency of 33 percent AMO. Efficiency of the same cell is just below 30 percent if the temperature is 500 K. The participants also noted that concentration was not required to achieve these levels. For example, the two-cell combination operating at 300 K would have an efficiency of 30 percent at 1 sun rather than 40 percent at 1000 suns. Similarly, the 24 cell limiting efficiency of 60 percent would be reduced at 50 percent as the concentration level is reduced from 1000 suns to 1 sun.

The participants saw no theoretical barrier to achieving efficiencies of about 50 percent with these approaches. They believed that the tandem approach was the most promising for achievement of high efficiencies.

Semiconductor systems that offer wide ranges of bandgap, lattice constants, electron affinities and other parameters of relevance to high efficiency cells are the first requirement. Quanternary alloys of the type $Al_xGa_{(1-x)}As_ySb_{(1-y)}$ seem attractive; however, the addition of antimony apparently results in poor performance cells due to low minority carrier lifetime. Another promising, but less developed, system is based on chalcopyrite semiconductors of the class Ia-IIIa-$(VIIa)_2$ and IIb-IVa-$(Va)_2$. However, the critical barrier is the ability to fabricate the required materials as free standing or epitaxially-grown layers on appropriate substrates. In terms of the number of different energy gap structures that could be built in a monolithic structure, the following ranking of processes was indicated:
MBE > MO-CVD > VPE > LPE. The most desirable process in terms of ease of use and cost appeared to be MO-CVD.

Characterization of raw materials was seen as a major problem. Other key problems were

accurate lifetime determination, characterization of the radiation tolerance and determination of actual operating temperatures. Critical cell problem areas are lifetime, lattice match, tunnel junction control and design and reduction of interface state densities.

The future of the monolithic tandem cell seems bright at this time. With funding from the DOE, USAF and NASA it is hoped that critical problem areas can be studied and overcome and that new generations of cells for space applications can be created.

Other possible high efficiency approaches were briefly discussed (electromagnetic wave energy conversion, light sensitive capacitors such as LaF_3 and high temperature thermophotovoltaic systems). Insufficient work has been done to date in these areas to warrant firm conclusions.

SUMMARY

Major conclusions of this conference can be summarized as follows:

1. 18 Percent AMO efficiency and 0.7 V open-circuit voltages are still achievable goals for silicon solar cells and warrant a continued, focussed effort.

2. The study of radiation damage from a fundamental defect-centered basis has been fruitful and should continue to be a major focus of work.

3. The gallium arsenide cell has the potential for 20 percent AMO efficiencies and offers the attractive possibility of a radiation insensitive power supply when operated at temperatures near 200° C.

4. Efficiencies in excess of 30 percent AMO can be achieved by monolithic, tandem cell designs without sunlight concentration and continued development on a broad front is warranted.

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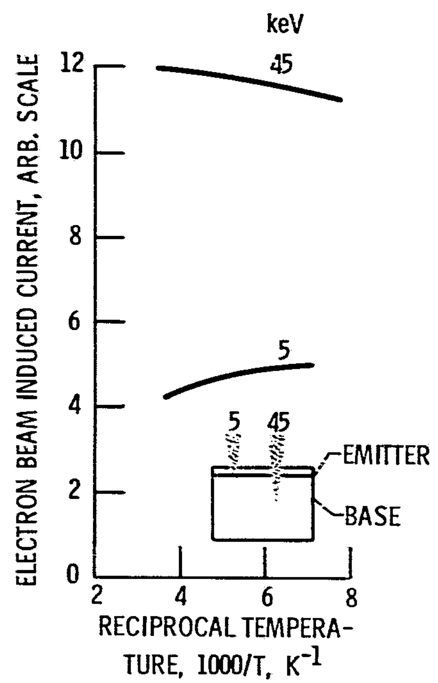

Figure 1. - Effect of temperature on the electron beam induced current in n^+p solar cell.

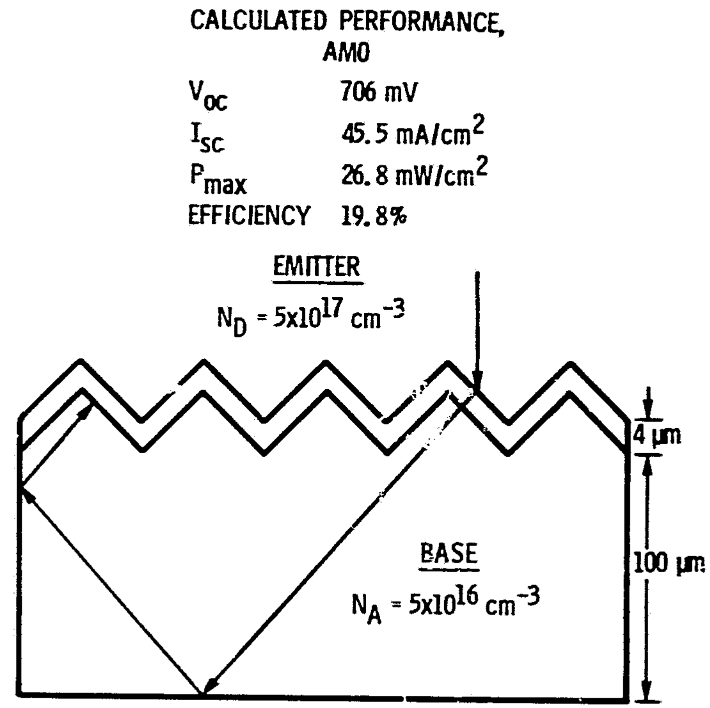

Figure 2. - Cross section of proposed high efficiency solar cell (3).

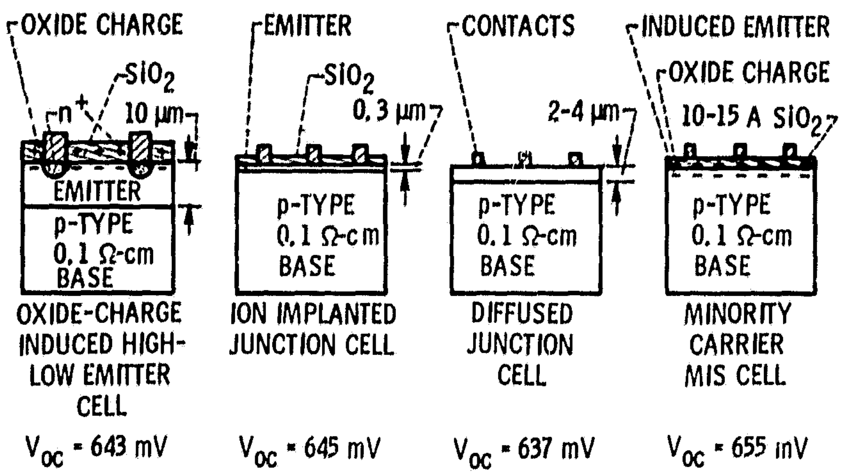

Figure 3. - Cross sections of high voltage silicon solar cells.

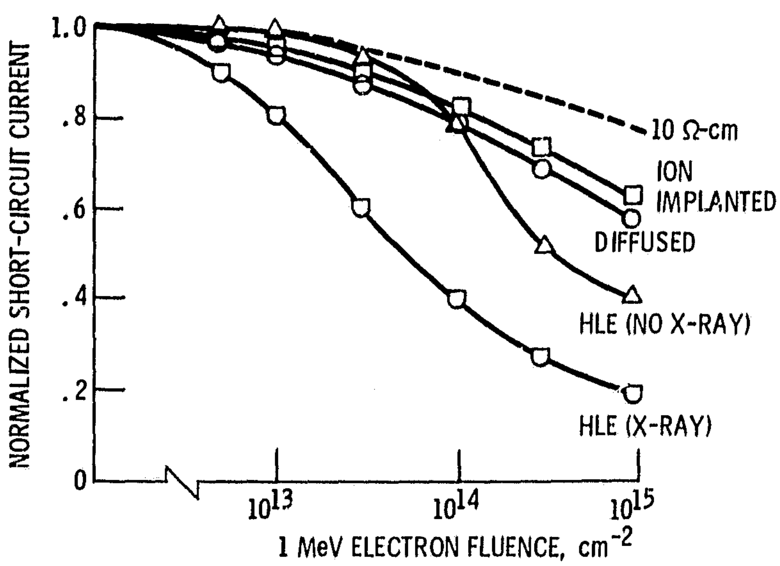

Figure 4. - Effect of 1 MeV electrons on cells with improved open-circuit voltage.

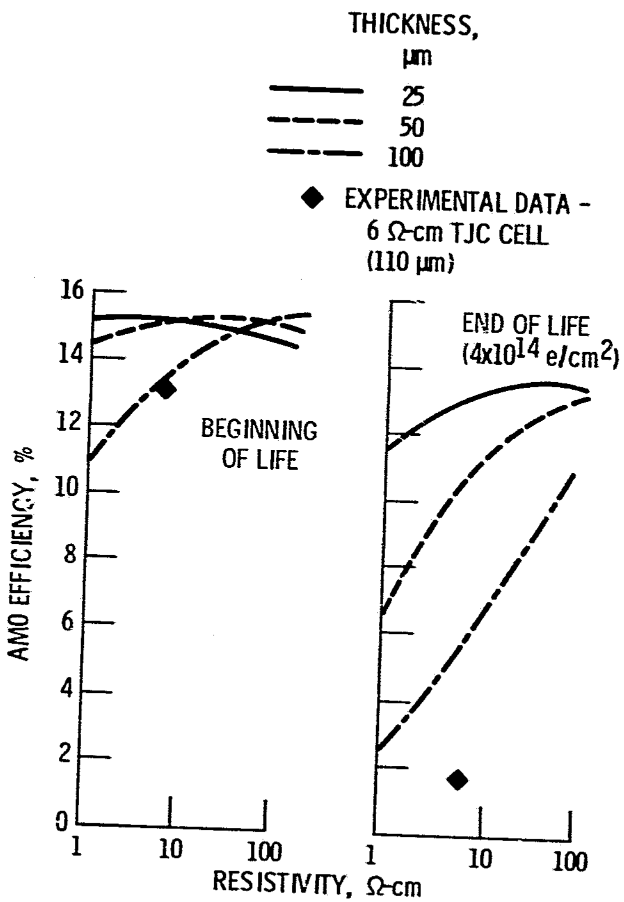

Figure 5. - Calculated performance of backwall cells.

DEFECT ENERGY LEVEL, eV	ELECTRON CAPTURE CROSS SECTIONS, cm^2 (12)	ATOMIC CONFIGURATIONS	
		MOONEY, ET AL. (13)	KIMERLING (14)
$E_V + 0.38$	$3x10^{-14}$	V-O-C	$C_I - C_S$
$E_c - 0.27$	$2x10^{-13}$	$B_I - O_I$	$B_I - B_S$
$E_V + 0.23$	$4x10^{-13}$	V-V	V-V

Figure 6. - Characteristics of key radiation-induced defects that reduce diffusion length in p-type silicon.

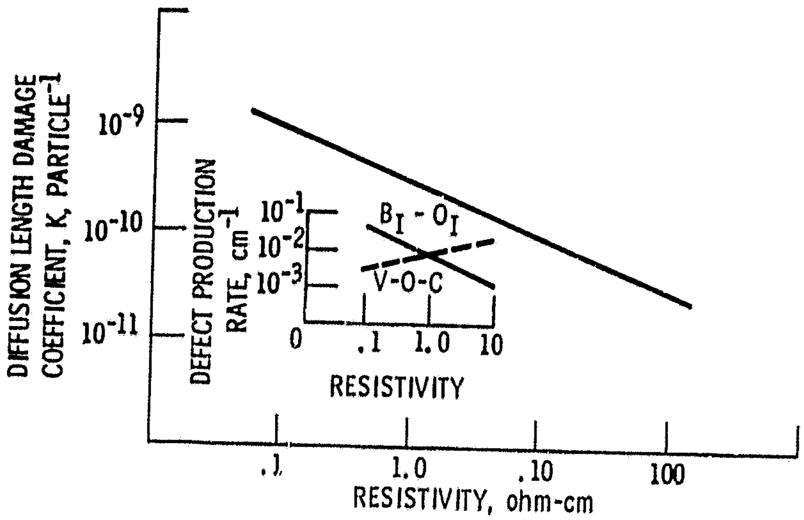

Figure 7. - Dependence of damage coefficient and production rate of key defect centers on resistivity.

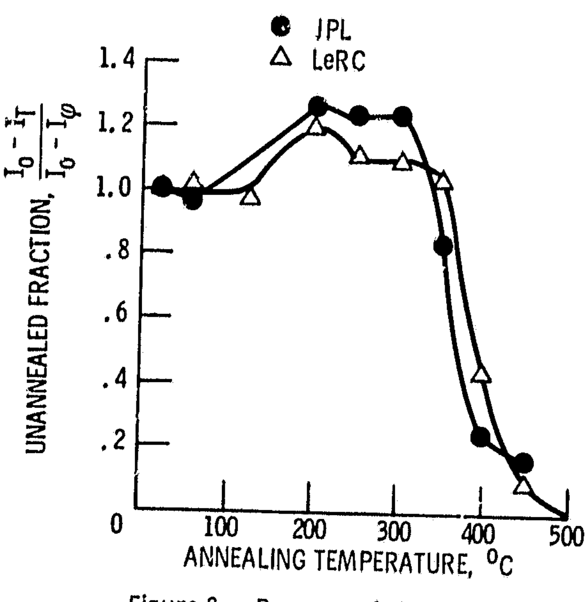

Figure 8. - Recovery of short circuit current in 2 Ω-cm silicon solar cells irradiated with 1 MeV electrons, t = 20 min, φ = 1x10^{15}.

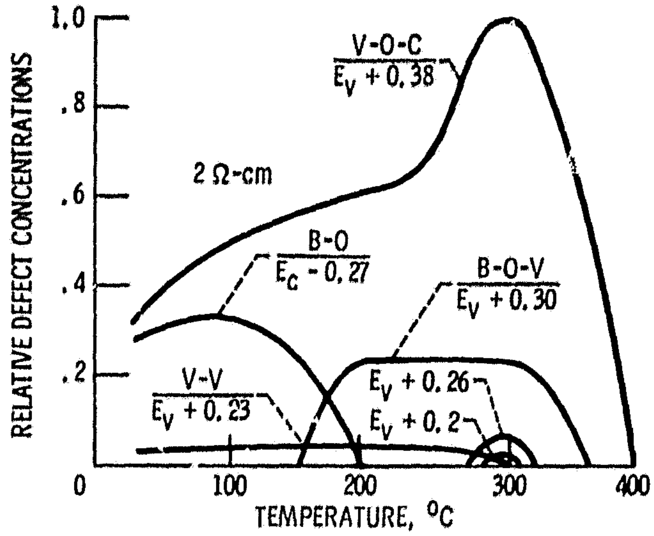

Figure 9. - Radiation induced defects in p-type silicon.

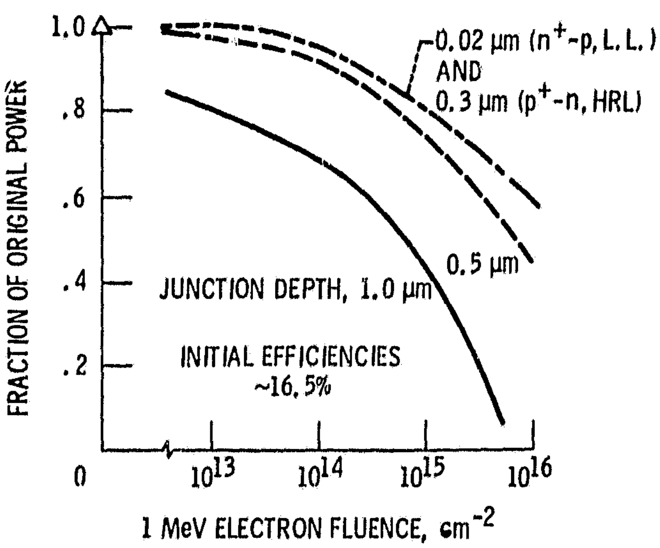

Figure 10. - Effect of junction depth on radiation damage in present GaAs solar cells.

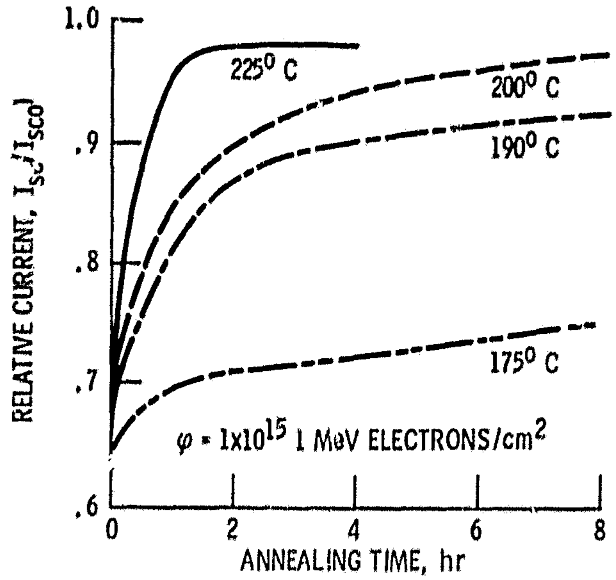

Figure 11. - Recovery of short circuit current with annealing time for GaAs solar cells.

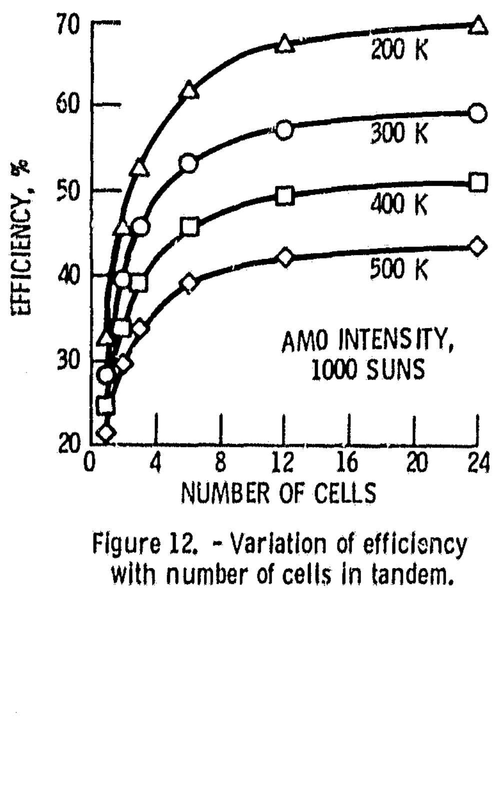

Figure 12. - Variation of efficiency with number of cells in tandem.

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15. Supplementary Notes

16. Abstract

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